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# (54) Pressure sensors

(57) Automatic (robot) machinery often incorporates hand-like equipment for grasping/gripping an object. One recurring difficulty is that of providing the hand with feedback enabling it to monitor the exact manner in which the hand is holding the object, specifically to provide useful data as to the shape of the object and its position relative to the hand.

The invention provides an area-extensive pressure sensor device, suitable for incorporation into a mechanical hand, that produces an output signal describing the spatial variation of the pressure applied to the device's sensory surface, by use of linear sequential scanning of the sensor surface to give, as a time-based output, a signal corresponding to the position-based pressure, the device comprising: a first, piezoelectric, layer (1) carrying a second, charge sensing, layer (6,7) the output of which is pressure dependent; means (4,2,22) for launching a deformation wave along the piezoelectric layer; and means (28,29,24) for correlating the sensor layer output with the position of the deformation wave.

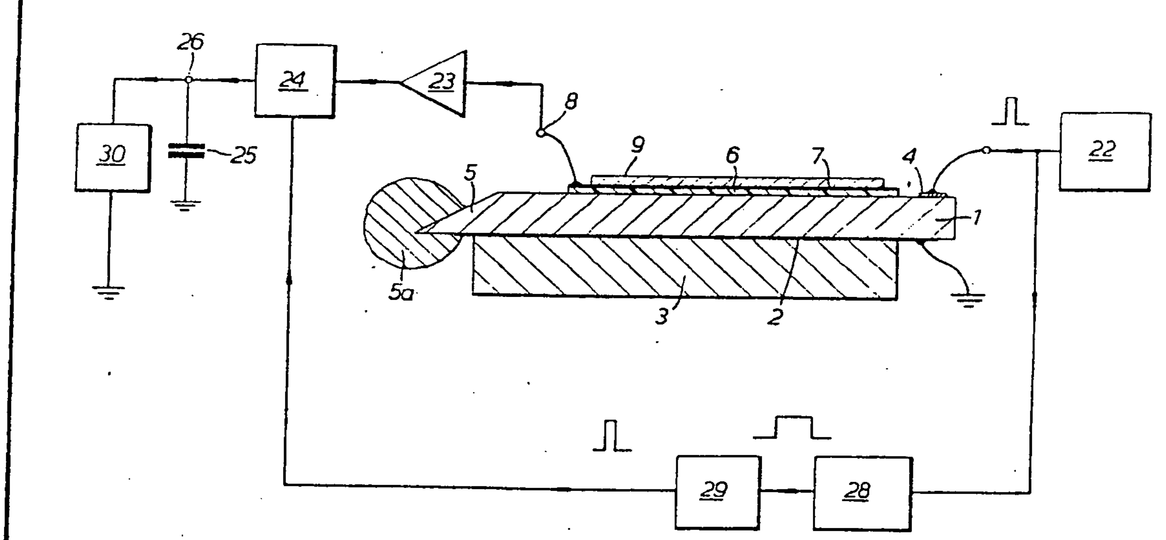


FIG.1.

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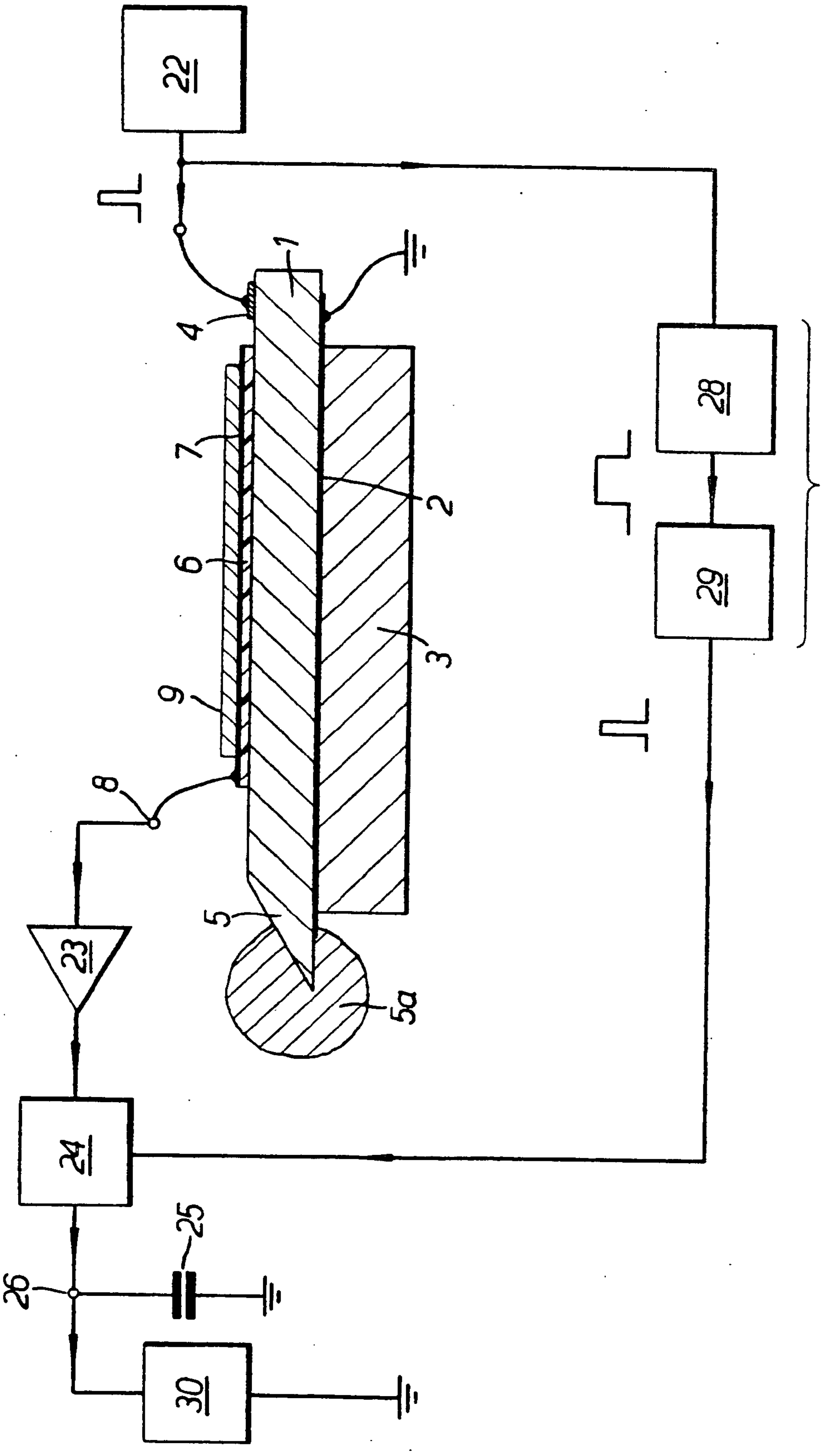


FIG.1.

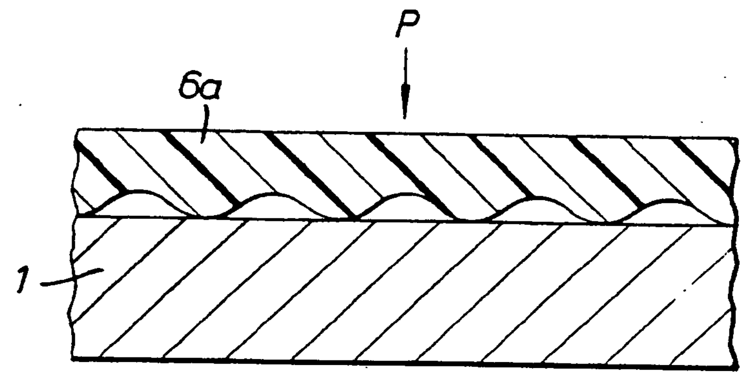


FIG.2A.

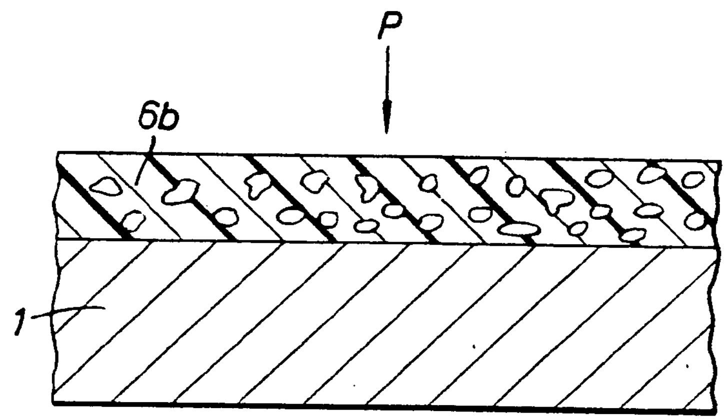


FIG.2B.

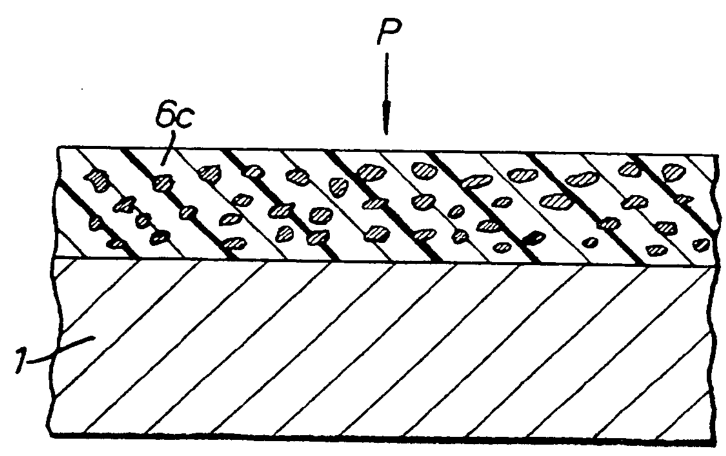


FIG.2C.

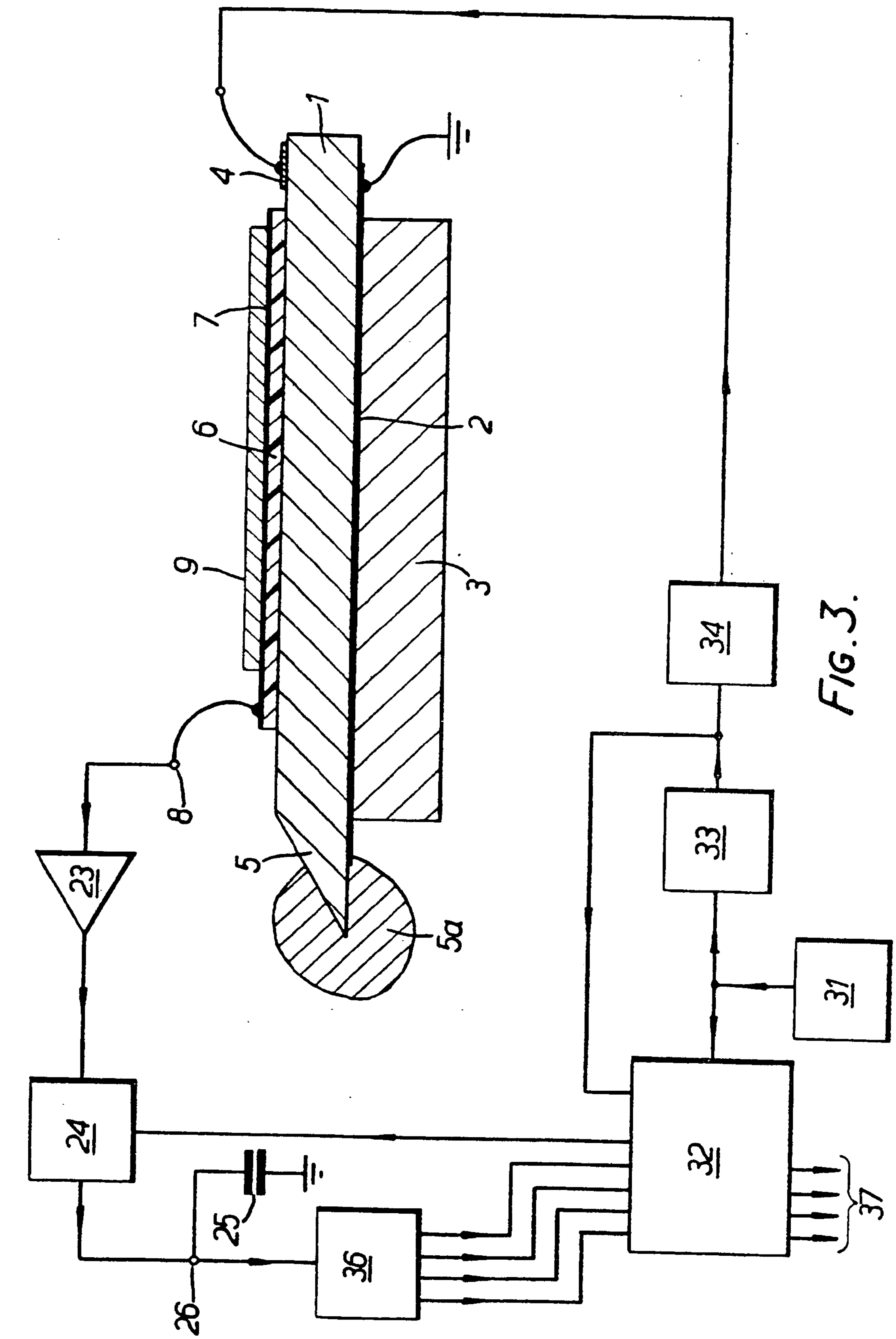


FIG. 3.

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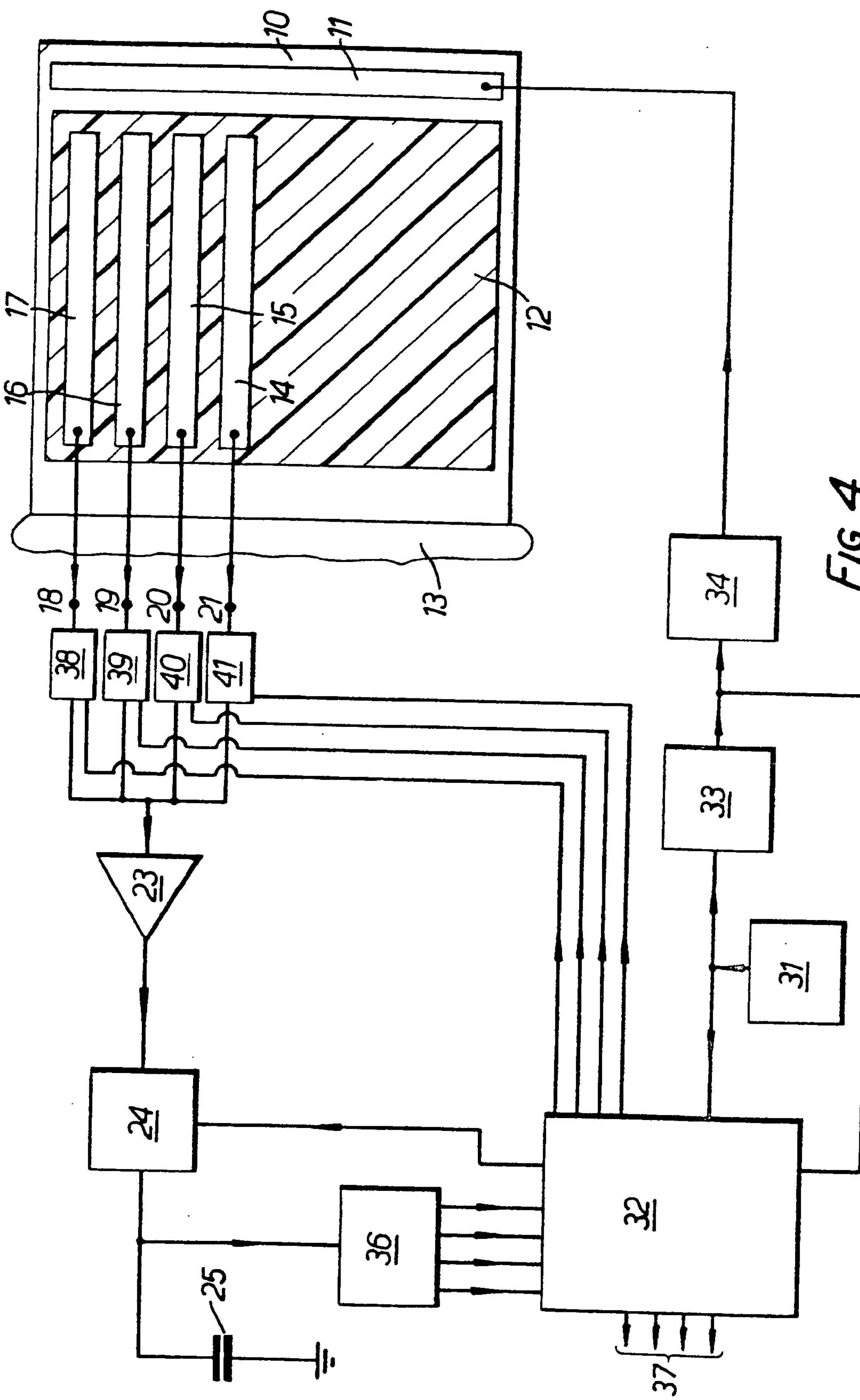


FIG. 4.

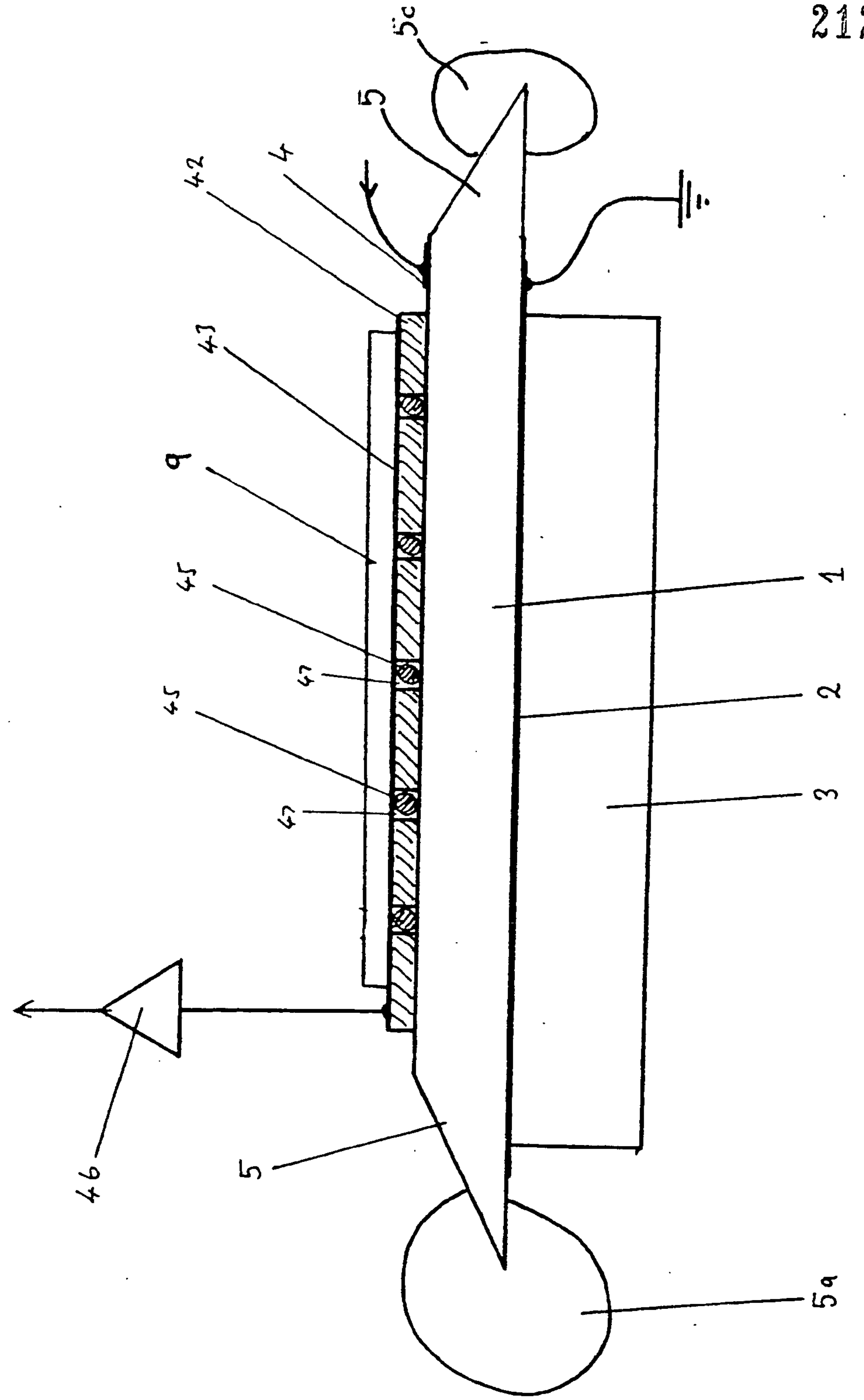


Figure 5

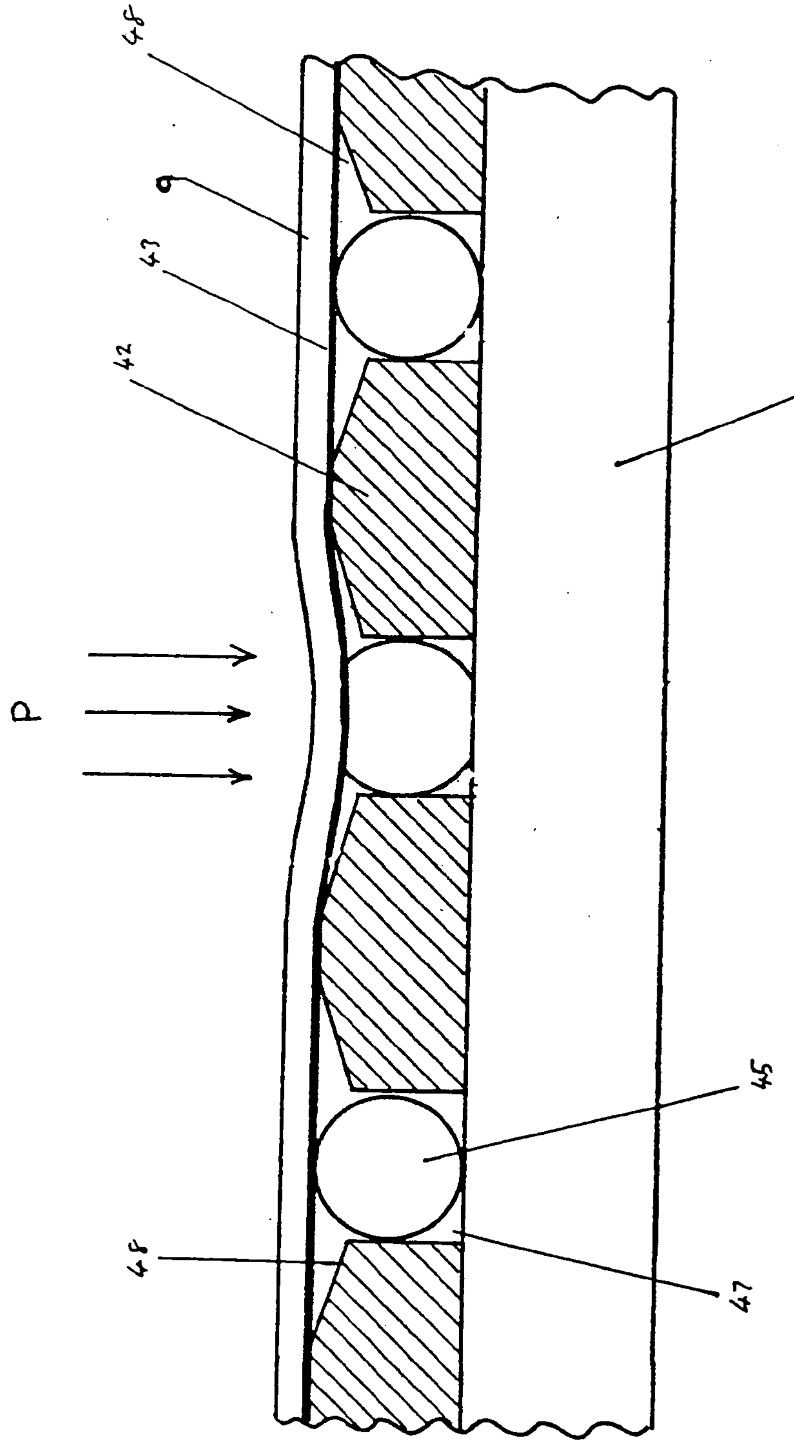


Figure 6

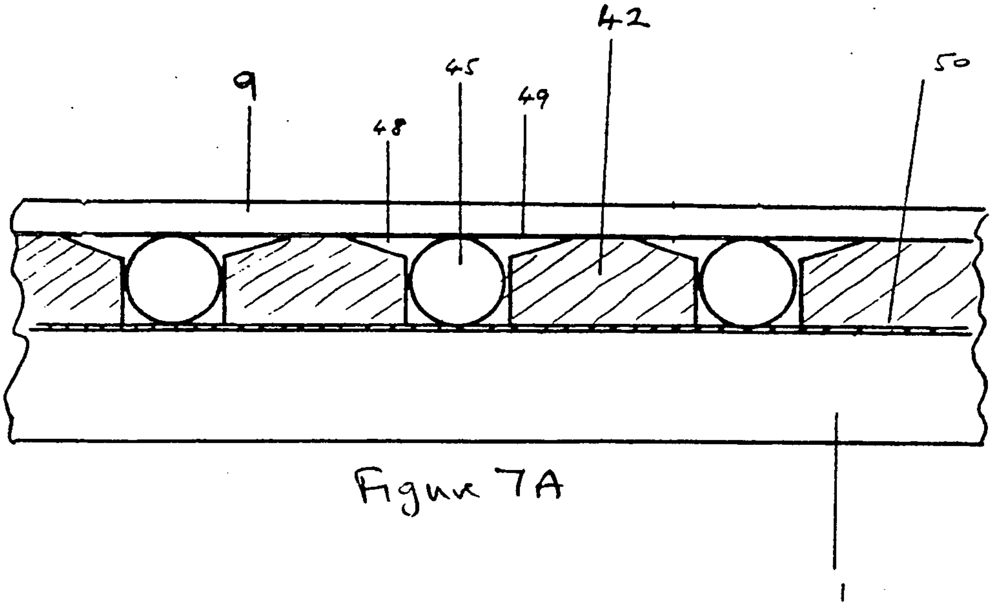


Figure 7A

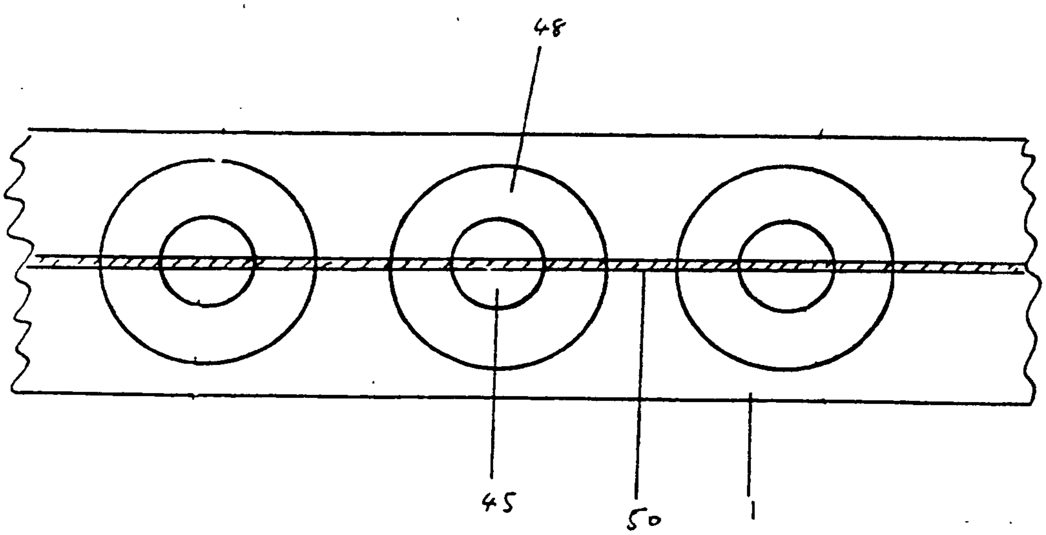


Figure 7B

SPECIFICATION
**Pressure sensors**

This invention concerns pressure sensors, and relates in particular to pressure sensing devices useful in connection with the hand-like grasping equipment of a robot or other such computer-controlled machine.

Modern automatic machinery of all types—ranging from a comparatively simple mechanical arm/hand combination up to a fully-fledged robot—often incorporates equipment, comparable to the human hand, for grasping/gripping an object preparatory to manipulating it in some way. Such a machine might, for example, be used to assemble a complex device such as an electric motor; the machine could pick the device's main component parts in succession out of a bin, or off a conveyor, orientate each correctly, and then place each in the appropriate position on the assembly as so far constructed.

One recurring difficulty in designing such an automatic machine is that of providing its hand-like equipment (referred to hereinafter for convenience simply as the hand) with some sort of feedback enabling it to monitor the exact manner in which the hand is holding the item the machine is manipulating. Some progress has been made in systems providing feedback concerning the pressure a simple pincer-like hand exerts on the item, but so far there has been little success in duplicating the ability of the human hand/brain combination to sense variations in applied pressure simultaneously over a relatively large area, and so derive useful data as to the shape of the item and its position relative to the hand. The present invention proposes one solution to this problem, by providing an area-extensive pressure sensor device, suitable for incorporation into a mechanical hand, that produces an output signal describing the spatial variation of the pressure applied to the device's sensory surface, the key to the device being the use of linear sequential scanning of the sensor surface to give, as a time-based output, a signal corresponding to the position-based pressure.

In one aspect, therefore, this invention provides a pressure sensor device comprising: a first, piezoelectric, layer carrying a second, charge sensing, layer the output of which is pressure dependent; means for launching a deformation wave along the piezoelectric layer; and means for correlating the sensor layer output with the position of the deformation wave.

In somewhat more expansive, but otherwise very similar, terms the invention may alternately be defined as a pressure sensor device, suitable for incorporation in a mechanical hand so as to output data concerning the spatial distribution of the pressure exerted between the hand and an object grasped thereby, which device comprises:

a first, piezoelectric, layer;

means for launching a deformation wave along the piezoelectric layer, to generate a travelling charge packet across the layer;

mounted face-to-face upon the piezoelectric layer, a pressure sensor in the form of a second, charge sensing, layer, this sensor layer giving an output the value of which varies as the pressure exerted by the device upon an object in contact with the sensor layer; and

means for correlating the sensor layer output with the position along the piezoelectric layer of the deformation wave/charge packet, thereby producing a device output signal describing as desired both the magnitude and the spatial distribution of pressure exerted between the device and the contacted object.

Before discussing in more detail the various parts of the device of the invention, it will perhaps be useful to consider how, in general, it works. The basis for the idea is that covering the relevant area there is a pressure sensor (the second, charge sensing, layer) that can be stimulated to output a signal in dependence upon the pressure exerted on it as it is sandwiched between the object being grasped and the first, piezoelectric, layer (beyond which will be a relatively rigid support provided either by the mechanical hand itself or by some suitable substrate), and that if at a known time the stimulation is applied at a known point then the sensor's output is a measure of the pressure at that point only. Accordingly, if, over a defined time period, the stimulation is similarly applied regularly at each of a sequence of known points, then as that time period occurs so point by point there is gathered from the sensor data relating to the pressure at each of the points in the sequence. In the device of the invention the regular stimulation at each of a sequence of known points during a known time period is achieved by launching a deformation wave into the device's piezoelectric layer; the velocity of the wave in the material of the layer is known (from measurements beforehand), as is the time at which it was launched, so that there may be calculated the wave's position along the device at any time after launch. Hence, as the wave progresses the device continuously outputs data allowing the calculation of the pressure exerted at the current position of the wave—and so there is attained a knowledge of the spatial distribution of the pressure exerted on/by the device from one end to the other.

The first layer of the device of the invention is a piezoelectric layer, and may be constructed with any appropriate shape, size and thickness. The layer dimensions will naturally depend to some extent upon the exact use to which the device is to be put (thus, for example, upon the type of mechanical hand to incorporate it), but generally an individual layer will be a narrow elongate strip (i.e., 1 mm wide by 20 mm long) and relatively thin (as is the case with most piezoelectric devices—e.g., 0.5 mm thick). However, where a mechanism requires the use of an area array of devices, the array can be either a series of individual strip-like devices side by side or (as may well be preferred) a single composite device

wherein the piezoelectric layer is wide enough to cover the entire area, but is then overlaid by individual strip-like sensors (such an arrangement is discussed in more detail hereinafter).

The material of which the piezoelectric layer is formed may be any suitable such material, though very preferably it is a relatively incompressible substance (for reasons explained hereinafter in connection with the sensor layer). Typical such piezoelectric substances are the piezoelectric ceramics based upon compounds like lead zirconate titanate, a specific example of this being that material supplied by Vernitron Ltd, of Southampton, under the designation PZT5A. Other materials suitable for use are lithium niobate, lead molybdate, crystal quartz,or Rochelle salt.

The first, piezoelectric, layer carries, mounted face to face thereon, a second, charge sensing, layer the output of which is pressure dependent—that is to say, the output of the sensor layer when it senses the pressure of an electrical charge varies (in some useful way, such as in amplitude) in accordance with the pressure being exerted across the opposed faces of the sensor. Though other ways of achieving this result are conceivable, a preferred way is to construct the sensor so that it is resiliently deformable in a direction normal to its faces—i.e., so that it may be squeezed flat, like a sponge, but will return to its unsqueezed thickness when the squeezing force is removed—and then to arrange that its ability to detect charge (and give an output signal relating thereto) is dependent upon its thickness. One possible arrangement involves constructing the sensor layer as the dielectric and one plate of a capacitor (the dielectric being the resiliently deformable portion), placing the sensor on the piezoelectric layer so that the former's dielectric portion is in contact therewith, and then connecting the plate atop the dielectric portion to means that can, be measuring the capacitance of the system, detect the presence of charge upon the near face of the piezoelectric layer. Naturally, as the external pressure exerted across the capacitor plate/dielectric layer/piezoelectric layer combination increases, squeezing the dielectric layer, and forcing the capacitor plate closer to any charge on the piezoelectric layer, then, provided that the piezoelectric layer itself is sufficiently incompressible not also to be deformed, so the capacitance, and thus the output of the sensor, is altered correspondingly. This arrangement requires the use of a dielectric layer that is resiliently deformable, and convenient materials for making such a layer are those dielectric materials that are inherently deformable, such as various rubbers (natural or synthetic), or similar rubber-like substances, and preferably that can in addition physically be shaped so as to provide a layer that is relatively easily deformed, such as a foamed layer or a ridged layer. Moreover, in order to "amplify" the effect caused by squeezing the dielectric layer, the layer material may be loaded with a particulate ferroelectric substance (such as barium titanate or lead zirconate titanate); the effective dielectric constant of the thus-loaded material is strongly dependent on the mean spacing of the ferroelectric particles, and squeezing the layer reduces that spacing, so significantly increasing the capacitance per unit area.

In the possible sensor layer arrangement just described, the layer is constructed as the dielectric and one plate of a capacitor. The plate may take the form of a simple conductive layer, this layer being conveniently of a metal, for example aluminium, foil suitable adhering to the dielectric, and apart from pointing out that its surface dimensions (length and breadth) naturally match those of the dielectric layer there is little else to say about it.

However, it should now be explained that this type of charge sensing layer results in a rather small output (typically of the order of a millivolt), and is therefore susceptible to interference from nearby electrical equipment. A more useful charge sensing layer (one that is both novel and inventive in its own right) is one that comprises an electrically insulating spacer layer carrying an elastically deformable diaphragm layer, the spacer layer having a plurality of via-holes therein each holding a deformable electrically conductive body in contact with the piezoelectric layer and reversibly squeezable between it and the diaphragm layer, to vary the area of that contact, dependent upon the external force applied across the device, the spacer layer also carrying on one or other surface an electrode layer in contact with the conductive bodies.

The preferred charge sensing layer incorporates an electrically insulating apertured spacer carried on the piezoelectric and itself carrying the diaphragm layer (the thickness of this spacer layer serving to keep the two apart). The via-holes in the spacer layer are large enough for the deformable bodies to sit therein without significant deformation until pressure is applied to the diaphragm layer. Naturally, the thickness of the spacer layer and the size and shape of its via-holes will all be matched to the size, shape and nature of the deformable bodies. However, in order that it may be easier to transfer the applied pressure from the diaphragm layer to the deformable bodies, so causing them more readily to deform, it is particularly preferred that each via-hole have generally a rather larger effective exit aperture on the diaphragm layer side than its effective diameter over the rest of the hole (a conical opening, with a cone angle near to 160°, seems very satisfactory). Such an aperture means both that the pressure need not be applied to the diaphragm layer immediately adjacent the body and also that the available movement of the diaphragm layer (and thus the degree of deformation of the body) will be the greater even for relatively small applied pressure.

The spacer may be of any suitable electrically insulating material. A typical such material is an

acrylic plastic—for example, one of the many rigid acrylonitrile-butadiene-styrene copolymers.

The spacer layer has a plurality of via-holes therein. The actual number of such via-holes depends upon the sizes of the holes and the extent of the spacer layer. In order, however, to obtain good resolution for the pressure sensor device there should be at least two via-holes per cm (about 5 holes per inch), and preferably there should be at least ten via-holes per cm (about 24 per inch). In one preferred embodiment described further hereinafter the via-holes are elongate channels, used with correspondingly elongate bodies, so giving potentially very high resolution in the direction of their length.

The preferred charge sensing layer employs a spacer layer carrying a diaphragm layer so that pressure on the diaphragm layer causes the bodies within the spacer layer's via-holes to be deformed. The diaphragm layer is a thin, flexible (resiliently deformable) plate—a diaphragm—extending over the area of the spacer layer, and it may be electrically conductive or insulating. Where, as discussed hereinafter, the charge sensor is of that type wherein the electrode layer contacted by the bodies is a thin strip electrode mounted "underneath" the bodies and in direct contact with the piezoelectric layer then the diaphragm layer is a separate component. However, where the charge sensor is of that type wherein the bodies are disposed between the piezoelectric layer and the electrode layer then, while it may still be a separate component, the diaphragm layer is itself conveniently used as the electrode layer, and must then be electrically conductive.

The diaphragm, when conductive, may be a thin layer of a metal (such as nickel or stainless steel) or a metallized plastics material (for example, aluminized Melinex—"Melinex" is a Registered Trade Mark for an ICI brand of polyester material, known in the US as "Mylar").

Each via-hole contains a deformable electrically conductive body connecting the electrode layer to the piezoelectric layer. As regards the body's deformability, this should be elastic, so that the body naturally returns to its undeformed state when the forces that caused it to deform are removed, and this will normally require the body to be made of an elastically deformable material (a conductive rubber, for example). However, one preferred possibility for the body material is a conductive liquid (specifically, mercury) in such small quantities that surface tension causes it to become in effect an elastically deformable globule. The body, therefore, is elastically (resiliently) deformable even if the material from which the body is made is not.

So far as concerns its electrical conductivity, two factors need to be taken into account. Firstly, each body needs to be conductive by comparison with the non-conductive nature of the spacer layer. Secondly, the impedance of the resistive path from the deforming face of the elastomer to the input electronics should be low in comparison with the impedance of the read portion of the piezoelectric layer, and in conjunction with the input impedance of the attached cabling and electronics it should not form a low-pass filter attenuating signals in the frequency range of interest. Resistivities of the order of $5\times10^{-3}$ ohm metres seem to be the required maximum, and material with resistivities of around $10^{-4}$ to $10^{-5}$ ohm metres, or less, are quite satisfactory.

Each body may be a liquid (in small globule form) or it may be an elastic solid. In the former case the liquid must be one that does not wet either the piezoelectric layer or the electrode layer (though conceivably each of these could have a thin surface layer of some anti-wetting agent), and that must be of a size in which surface tension controls the shape of the body when unconstrained (forcing it into a sphere) and gravity and inertia have no significant effect. A range of suitable liquid globule sizes is from 0.2 to 1 mm, 0.5 mm being quite acceptable.

Where each body is a deformable solid (a conductive rubber, for example) it too may be in globule—spherical—form. Alternatively, and provided means are employed to maintain the body's orientation, it may be conical, frusto-conical or hemispherical (with the top of the cone, or the rounded surface of the hemisphere, directed towards the piezoelectric layer), and in such a case that portion of the body directed away from the piezoelectric layer—thus, the base of the cone/hemisphere—may be secured to, or even contiguous with, the diaphragm layer. One other form for the body when solid is elongate cylindrical (of circular, perhaps D, cross-section), disposed with its axis parallel to the plane of the dielectric. This form has the advantage that in the direction of its length it allows the device to have extremely high resolution (limited either by the electrode spacing or—if extending in the direction of propagation of the deformation wave—by the length of each individual deformation pulse).

The material from which the body is made may be a liquid or a solid. A possible liquid is mercury, although some conductive ionic liquids/solutions may be usable, while a possible solid is an electrically conductive elastomer composed of a rubbery material with a filler of conductive particles. The material Cho-Seal 1250 manufactured by Chomerics Inc. of Woburn, Massachusetts, is such a material, being a silicone elastomer "filled" with silver-plated copper particles.

The piezoelectric layer is electrically connected to the electrode layer by the conductive deformable bodies. There seem at present to be two rather different ways in which this electrode layer may be disposed. In the first, and perhaps more conventional, the electrode layer is spaced apart from the piezoelectric layer by the spacer layer, and the bodies are positioned between and in contact with the two. In this case the electrode layer is conveniently sheet-like, extending over the whole area of the device. However, in the

second the electrode layer is on the piezoelectric layer side of the spacer layer, so it actually contacts the piezoelectric layer already, but is in the form of a narrow strip, and each body is positioned "on top" of and in contact with both this electrode strip and the piezoelectric layer. In either case, when the bodies are deformed by being squashed their contact area with the piezoelectric layer increases and so the charge transfer capability of the charge sensing element increases correspondingly (and, of course, when the bodies are caused to return to their undeformed shape the contact area and the charge transfer capability both decrease accordingly).

The surface dimensions of the sensor layer naturally match those of the underlying piezoelectric layer, and thus the sensor layer is also a thin elongate strip.

In order to protect the sensor device from the relatively harsh environment (on a mechanical hand) in which it may be employed, the sensor layer is very preferably covered in a tough, hard but flexible, thin outer layer. Indeed, the whole of the exterior surface of the device is conveniently covered by this outer layer. A typical material for such an outer layer is a silicone elastomer about 0.1 mm thick.

The second, charge sensing, layer provides an output which is dependent upon the pressure across the layer, and for useful information to be derived from this the sensor layer needs to be connected up to suitable means for detecting and acting upon that output. One convenient such means, described in more detail hereinafter with reference to the accompanying drawings, uses a voltmeter to measure the voltage across a storage capacitor charged up by an amplified version of the charge sensing layer's output.

The sensor device of the invention causes a ripple of charge to pass along the surface of the piezoelectric layer by causing a deformation wave similarly to travel along the layer. As the piezoelectric material is deformed by the wave so a piezoelectrically-generated charge packet is developed across the layer, and as the wave travels along the layer so does the charge packet. The device employs means to launch the deformation wave into and along the piezoelectric layer, and very conveniently this means is merely electrodes positioned at one edge of the layer and on either main surface thereof (so that they sandwich the layer between them), these electrodes being connectable to a source of electrical voltage that can be used to generate a like voltage across the electrodes, so resulting in a piezoelectric deformation of the layer material. Naturally, this deformation will be transmitted through the piezoelectric material at a known velocity characteristic of that particular piezoelectric, so causing the required deformation wave to progress therethrough. Clearly, if the applied voltage is in the form of a single pulse, specifically a sharp step from one level to another, and ignoring any reflection off the launch end of the piezoelectric layer, then a like sharp, well-defined, single deformation wave will travel along the piezoelectric layer, and knowing the wave velocity so the position of the wave at any time after its launch can be calculated. Thus, for example, a 20—30 volt pulse with a 0.25 microsecond or less rise time results in a satisfactory deformation "wave" with an effective length of about 1 mm in a conventional lead zirconate titanate piezoelectric layer, and repeating this 1000 times per second provides a useful output.

In operating the sensor devices of the invention a deformation wave is launched into the piezoelectric layer. This wave travels along the layer, and will eventually reach that layer edge "opposite" where it was launched. In addition, of course, a like deformation wave also travels in the opposite direction, reaching that layer edge adjacent the launch position. In each case, unless steps are taken to prevent it, some—and possibly a significant proportion of—the wave will be reflected off the interface between the layer and the surrounding medium, and, progressing back along the layer, may result in some confusion as to what pressure is where. Though this difficulty could be dealt with in the electronics of the system using the device, it is nevertheless preferable to avoid it by constructing each edge of the layer with a wedge shape, and then placing around the wedge a wave-absorbent buffer that soaks up the remaining wave energy and so prevents any, or any substantial, reflected wave being formed. Apart from being strongly absorbent of the wave energy the buffer should have a mechanical impedance matching that of the piezoelectric layer. An example of a suitable buffer material for absorbing wave energy at ultrasonic frequencies is indium or an alloy thereof.

As the deformation wave travels along the piezoelectric layer, its position computable from a knowledge of its launch time and its velocity in the layer, so there is generated a like travelling charge packet on the layer surface whose position at any time is the same as the wave's. Moreover, as the charge packet travels over the piezoelectric layer's surface so the charge sensitive sensor layer provides a time varying output caused by that charge packet, the value of that output varying in dependence upon the local pressure (at the charge packet position) across the sensor layer. By correlating the time based sensor output with the time based wave/packet position, so there may be derived a measure of the magnitude of the applied pressure all along the device as a function of the position along the device. An electronic arrangement for effecting this correlation (by time gating the sensor output) is described in more detail hereinafter with reference to the accompanying drawings.

The invention extends, of course, to a mechanical hand (or like apparatus), whenever employing a pressure sensor device as described and claimed herein.

Various embodiments of the invention will now be described, though only by way of illustration, with reference to the accompanying drawings in which:—

Figure 1 is a diagrammatic vertical cross section through a pressure sensor device in accordance with the invention, showing in addition an electronic circuit (in block form) suitable for driving the device and processing its output signals;

Figures 2A, B and C are diagrammatic vertical cross sections through different sensor layers useful in a device like that of Figure 1;

Figure 3 is a more complex version of the device and circuitry of Figure 1;

Figure 4 is a diagrammatic top plan view of another sensor device of the invention (without its protective cover layer), showing in addition an electronic circuit (in block form) suitable for driving the device and processing its output signals;

Figure 5 is a diagrammatic vertical cross section through a pressure sensor device of the invention employing a charge sensing layer having a plurality of deformable bodies within the via-holes of a spacer layer;

Figure 6 is a larger-scale view of part of Figure 5; and

Figures 7A and B are respectively top plan and vertical cross sectional views through a modified version of the charge sensing layer of Figure 5.

The device of Figure 1 comprises a strip (1) of piezoelectric material mounted, via a matching earthed strip electrode (2), on a rigid substrate (3), and carrying a squashy dielectric layer (6) itself supporting, via a matching strip electrode (7), a matching protective cover layer (9); in this Figure the cover layer is for clarity shown extending only over the electrode 7 and dielectric layer (6). At one end of the piezoelectric strip 1 is a small electrode (4) attached to the face opposed to the earthed strip electrode 2, this enabling ultrasonic pulses to be launched into the piezoelectric strip 1 by the application of voltage pulses at ultrasonic frequencies to the small electrode 4. Pulses launched into the piezoelectric strip 1 travel along the strip to its opposite end, where they are absorbed by a wedge (5) surrounded by an absorbing material (5a).

The pressure (P) to be monitored is applied to the exposed surface of the cover strip 9. As a pulse travels through the piezoelectric strip 1, a travelling surface charge is built up at the interface between that strip and the dielectric strip 6, which charge induces a voltage on the electrode 7 that is proportional to the capacitance per unit area of dielectric 6 in the immediate vicinity of the pulse. Because the applied pressure P squashes the dielectric strip 6 in parts (but not in others), the capacitance is a function of the pressure, so that the voltage induced in the electrode 7 (monitored by voltage sensing means through terminal 8), is a time-sequential replica of the variation of pressure P along the path of the pulse.

The dielectric layer 6 in Figure 1 may have a number of possible structures, examples being shown in Figures 2A, B and C. In Figure 2A, the layer 6 consists of an elastomer layer (6a) that has an array of ridges embossed in the lower surface. The ridges are in contact with the piezoelectric strip 1 so that when pressure is applied to the elastomer layer 6a the ridges are compressed and its thickness is reduced. The capacitance per unit are of the layer is therefore increased roughly in proportion to the pressure.

Another dielectric material is shown in Figure 2B. It consists of an elastomer layer (6b) containing a large number of small gas bubbles which are compressed when pressure is applied, reducing the layer thickness. The capacitance per unit area is therefore a function of the applied pressure.

Yet another dielectric material is shown in Figure 2C. It consists of an elastomer layer (6c) containing granules of a ferroelectric material; if the granules are closely packed together in such a material the effective dielectric constant of the layer is strongly dependent on the mean spacing between granules. Applied pressure will reduce the mean spacing and so increase the capacitance per unit area.

A suitable electronic circuit for driving the sensor device of Figure 1 and processing its output signals is also shown in Figure 1. A pulse generator (22) feeds voltage pulses into electrode 4 at a suitable pulse repetition frequency. The pulse rise time is determined by the required spatial resolution of the sensor: the shorter the rise time the smaller the space occupied by the ultrasonic pulse while travelling through piezoelectric material 1, and so the higher the spatial resolution of pressure measurement. A suitable pulse rise time is about 0.25 microsecond, giving a spatial solution of about 1 mm. A suitable voltage pulse level is 20 to 30 volts, possibly 5 to 50 volts, with a pulse repetition frequency of 1 kHz.

The output voltage from terminal 8 has a time-varying component corresponding to the surface pressure variations along the path of the ultrasonic pulse, with a typical peak-to-peak variation of about 10 millivolts. This is amplified by an amplifier (23) to give a peak-to-peak output signal of about 2 volts. The output of amplifier 23 is fed to the input of a fast analogue gate (24) which has a response time $<100$ nanoseconds. The output of gate 24 is connected to a storage capacitor (25; say, 100 picofarads) which is also connected to an output terminal (26). The gate input of analogue gate 24 is driven by the input pulses applied to electrode 4 via a variable time-delay circuit (27) of conventional design, consisting of a variable pulse length monostable multivibrator (28) triggered by the pulses from pulse generator 22, the multivibrator's output pulse length being equal to the time delay required. The trailing edges of the output pulses from the multivibrator 28 are used to trigger a second monostable multivibrator (29) which

produces output pulses of a duration equal to that of the output of pulse generator 22 (say, 0.25 microsecond). The time delay of circuit 27 is adjusted to be equal to the time taken for ultrasonic pulses generated at electrode 4 to travel through piezoelectric material 1 to the point at which pressure measurement is required.

On receipt of a gating pulse, the analogue gate 24 momentarily connects the output of amplifier 23 to storage capacitor 25 which charges up substantially to the full voltage of the output of amplifier 23. The voltage accumulated on capacitor 25, which is retained after the gating pulse is removed, is measured by means of a high input impedance voltmeter (30) also connected to terminal 26. This voltage is indicative of the surface pressure applied to the sensor at the chosen point of measurement. An output indicative of the surface pressure at other positions on the sensor surface can be obtained by an appropriate adjustment of time-delay of circuit 27.

In practical applications—for example, in sensing the position and gripping force of objects picked up by a robot hand—an automatic means for sequentially taking measurements of pressure at different points on the sensor device, and accumulating the results in a computer memory, would be employed. Under these circumstances the variable time-delay circuit 27 would need to be electrically adjustable, and controllable under the direction of a computer, so it would be more convenient to have the time-delay function of circuit 27 synthesized within the computer itself by counting the internal clock pulses under the direction of the computer programme. Circuitry required for such an operation is shown in Figure 3. A clock pulse generator (31), which conveniently runs at a frequency of about 4 MHz, supplies clock pulses to a digital computer (32) which includes a central processor and a random-access memory (not shown separately). The output of clock pulse generator 31 is divided in frequency by a factor N by means of a divider circuit (33), the factor N being chosen to produce an output frequency equal to the input pulse repetition frequency required by the sensor (say, 1 kHz). The output of the divider circuit 33 is fed to the tripper input of a monostable multivibrator (34) which produces output pulses of the duration required for driving the sensor device (say, 0.25 microsecond). The output of the multivibrator 34 is fed to the device input electrode 4, while the output of the divider circuit 33 is fed to an input of the computer 32 which generates a time-delayed replica of the input pulse which is fed to the gate input of analogue gate 24. The output of the sensor from terminal 8 is fed to the input of analogue gate 24 as before, and is stored in capacitor 25 as before. The voltage on terminal 26 connected to the capacitor 25 is applied as an analogue input to an analogue/digital converter (36) which provides a digital (serial or parallel) input to the computer 32 equivalent to the analogue output voltage of the sensor device. The computer then stores this digital information, makes a number of measurements in sequence of surface pressure at different points on the sensor (and stores the results), then makes appropriate calculations on the stored information to determine the size and position of the object being gripped and the magnitude of the gripping force, and produces appropriate output signals through output terminals (37) to control the position and gripping force of the mechanical hand.

The pressure sensor device shown in Figure 4 is one that can detect spatial variation in pressure in two dimensions. Basically, it is like a number of the Figure 1 devices placed side by side (like fingers on a hand). A piezoelectric plate (10) has an electrode (11) at one end to which voltage pulses are applied launching ultrasonic pulses into the plate. The pulses are absorbed at the opposite end of the plate by an absorber (13). A pressure sensitive dielectric layer (12), having a structure generally similar to one of those described with reference to Figures 2A, B or C, is placed on top of plate 10. Electrode strips (as 14, 15, 16, 17), extending to any required number, are placed on top of the dielectric layer 12, and are connected each to the voltage sensing means through individual terminals (18, 19, 20, 21). A protective layer (not shown) is placed on top of the electrodes.

An output voltage will be produced at each of the terminals 18—21 in the form of a time sequential voltage proportional to the spatial variation of pressure applied to the sensor surface in the immediate vicinity of each of the electrodes 14—17. If a sufficient number of electrodes is employed coupled to a sufficient number of voltage sensors, the spatial variation of surface pressure over the whole of the sensor surface can be measured.

The electronic circuitry needed to drive such a two-dimensional sensor device, and to process its output signals, is also shown in outline in Figure 4. The circuit is identical to that shown in Figure 3 except that an electronic switching means is incorporated between the various output terminals of the sensor (18, 19, 20, 21 etc.) and the input of amplifier 23. The switching means comprises a series of analogue gates (38, 39, 40, 41 etc.) which are switched on and off sequentially by control signals from computer 32. When a first acoustic pulse is generated in piezoelectric plate 10 by a voltage pulse applied to electrode 11, analogue gate 38 is simultaneously switched on by a control signal from the computer 32. All the other analogue gates 39, 40, 41 etc. are switched off during this period. The system then functions, as explained with reference to Figure 3, to store signals in the computer 32 giving details of the pressure distribution over the area covered by electrode 17. When this has beem completed, analogue gate 39 is switched on and analogue gate 38 is switched off by a control signal from the computer, and the process is repeated to store

details of the pressure distribution over the area covered by electrode 16. This procedure is then repeated for all the remaining electrode strips 14, 15 etc., until data covering the pressure distribution over the whole area of the sensor is obtained. This data is then processed by the computer to establish the size and orientation of the object in contact with the sensor surface and the magnitude of the gripping force. Appropriate output signals are then generated through terminal 37 to control the position and gripping force of the mechanical hand.

Figures 5 and 6 together show details of an inventive pressure sensor device using the preferred charge sensing layer.

As in Figure 1, the device consists of a strip of piezoelectric material 1 with electrodes 2, 4 attached, mounted on a suitable substrate 3 (though each end 5 is wedge shaped, and has a suitable absorber 5a), all substantially the same as described with reference to Figure 1. However, in place of the squashy dielectric layer (6 in Figure 1) is a layer (42) of rigid electrically insulating material containing an array of via-holes (as 47). On top of the insulating layer 42 is a diaphragm layer (43) of deformable electrically conducting material, and on top of the diaphragm 43 is a protective cover layer 9. In each of the enclosed spaces formed in the via-holes 47 between the piezoelectric strip 1 and the conducting layer 43 is placed a droplet of mercury (45). The droplet diameter is precisely controlled so that in the absence of applied pressure the droplet is just in contact with the piezoelectric strip 1 and the conducting layer 43, forming an electrically conductive path between the two. When pressure is applied to the exposed surface of the protective cover layer 9 the conducting layer 43 deforms, and the mercury droplet 45 becomes squashed, increasing the area of contact between the droplet and the surface of the piezoelectric strip. A travelling surface charge wave caused by an ultrasonic pulse travelling through the piezoelectric strip therefore produces a charge in the mercury droplet 45 and the conductive layer 43 proportional to the area of contact between the droplet and the piezoelectric surface. The conductive layer is connected to the input of a charge amplifier (46) which consequently receives a charge pulse proportional to the area of contact between the droplet and the piezoelectric surface. As the area of contact is dependent on the applied pressure, the amplitude of the output voltage from charge amplifier 46 varies with the applied pressure.

The area around each mercury droplet 45 is an individual pressure sensing cell, and the device consists in effect of a line of such cells scanned sequentially by a travelling ultrasonic pulse. All the cells are connected to a common conducting layer 43 and a common charge amplifier 46, and the output from this charge amplifier is a sequence of voltage pulses corresponding to the outputs from each cell, each pulse having an amplitude dependent on the locally applied pressure.

The output signal is processed and stored by electronic circuitry substantially the same as that shown in Figure 3.

The main advantage of this type of sensor over types employing deformable dielectric layers is that a much larger charge is coupled into the output electrode as a result of the use of a conductive path between the piezoelectric and the output electrode.

A more detailed description of the construction of the charge sensing layer is now given with reference to Figure 6. The mercury droplets 45 are of a small size (typically 0.5mm) so that surface tension forces constrain them into a substantially spherical shape when no external force is applied to deform them. The dimensions of the holes 47 in the electrically insulating layer 42 are made roughly equal to the droplet diameter so that the droplets are restrained from physical movement. This means that the hole diameter must be roughly equal to the thickness of layer 42. For mercury droplets of this size surface tension forces are much larger than gravitational or inertial forces produced by physical movement, unless these forces are exceptionally violent, so the droplets will retain their spherical shape irrespective of changes in orientation or bodily displacement of the sensor; therefore no spurious output signals will be produced by such movements.

The construction materials of the cells (piezoelectric strip 1, insulating layer 42, and deformable conductive layer 43) are chosen so that they are not wetted by mercury and do not react chemically with mercury. A lead zirconate-titanate (PZT) ceramic is suitable for the strip 1, an acrylonitrile-butadiene-styrene is suitable for the insulating layer 42, and a stainless steel is suitable for the deformable conductive layer 43.

An increase in sensitivity to applied pressure can be obtained by reducing the area of contact between the insulating layer 42 and the deformable conductive layer 43, and hence increasing the unsupported area of the latter. This results in an increase in the deformation of the deformable layer by applied pressure (P), in the deformation of the mercury droplet 45, and hence in the change in output signal per unit pressure. One method for doing this is to produce conical indentations (as 48) in the surface of the insulating layer 42 coaxial with the holes 45.

A modification which removes the need for a deformable conductive layer 43 is shown in Figures 7A and B. In place of deformable conductive layer 43 is a deformable insulating layer (49). The rest of the construction is as described previously with reference to Figures 5 and 6, with the exception of a thin electrically conductive track (50) which is laid down on the surface of piezoelectric strip 1 in a position where it is in contact with the mercury droplets 45 (this is shown more clearly in the plan view of the sensor shown in Fig. 7B). Track 50 performs the

same charge collection function as deformable conductive layer 43 but has the advantage that it does not need to be both electrically conductive and deformable. If the width of track 50 is made constant and much smaller than the diameter of mercury droplets 45, the electrical charge picked up directly by track 50 from piezoelectric strip 1 will be small and constant in comparison with that "varying" charge picked up via the mercury droplets 45, so the output signal obtained from track 50 will be substantially all produced by pressure-dependent deformation of the droplets 45.

The sensors described above with reference to Figures 5, 6, 7A and 7B are all one-dimensional in that they are able to measure the distribution of pressure along one axis only. The distribution of pressure over an area may be obtained by placing a number of such one-dimensional sensors side by side and connecting them to electrical circuitry substantially the same as that described with reference to Figure 6.

## Claims

1. A pressure sensor device comprising: a first piezoelectric, layer carrying a second, charge sensing, layer the output of which is pressure dependent; means for launching a deformation wave along the piezoelectric layer; and means for correlating the sensor layer output with the position of the deformation wave.

2. A pressure sensor device as claimed in claim 1, suitable for incorporation in a mechanical hand so as to output data concerning the spatial distribution of the pressure exerted between the hand and an object grasped thereby, which device comprises:

a first, piezoelectric, layer;

means for launching a deformation wave along the piezoelectric layer, to generate a travelling charge packet across the layer;

mounted face-to-face upon the piezoelectric layer, a pressure sensor in the form of a second, charge sensing, layer, this sensor layer giving an output the value of which varies as the pressure exerted by the device upon an object in contact with the sensor layer, and

means for correlating the sensor layer output with the position along the piezoelectric layer of the deformation wave/charge packet, thereby producing a device output signal describing as desired both the magnitude and the spatial distribution of pressure exerted between the device and the contacted object.

3. A device as claimed in either of the preceding claims, wherein the piezoelectric layer is a narrow, elongate, and thin, strip.

4. A device as claimed in either of claims 1 and 2 which is an area array device, wherein the piezoelectric layer is wide enough to cover the entire area, and is then overlaid by individual strip-like sensor layers.

5. A device as claimed in any of the preceding claims, wherein the piezoelectric layer is formed of a ceramic based upon lead zirconate titanate.

6. A device as claimed in any of the preceding claims, wherein the sensor layer is so constructed that it is resiliently deformable in a direction normal to its faces, and its ability to detect charge (and give an output signal relating thereto) is dependent upon its thickness.

7. A device as claimed in claim 6, wherein the sensor layer is constructed as the dielectric and one plate of a capacitor (the dielectric being the resiliently deformable portion), and is placed on the piezoelectric layer so that the former's dielectric portion is in contact therewith, the plate atop the dielectric portion being connectable to means that can, by measuring the capacitance of the system, detect the presence of charge upon the near face of the piezoelectric layer.

8. A device as claimed in claim 7 wherein the sensor layer capacitor plate is in the form of a simple conductive layer of metal foil.

9. A device as claimed in any of claims 1 to 5, wherein the charge sensing layer comprises an electrically insulating spacer layer carrying an elastically deformable diaphragm layer, the spacer layer having a plurality of via-holes therein each holding a deformable electrically conductive body in contact with the piezoelectric layer and reversibly squeezable between it and the diaphragm layer, to vary the area of that contact, dependent upon the external force applied across the device, the spacer layer also carrying on one or other surface an electrode layer in contact with the conductive bodies.

10. A device as claimed in claim 9, wherein each via-hole has a generally rather larger effective exit aperture on the diaphragm layer side than its effective diameter over the rest of the hole.

11. A device as claimed in either of claims 9 and 10, wherein each deformable body is a globule of liquid from 0.2 to 1 mm in diameter.

12. A device as claimed in either of claims 9 and 10, wherein each deformable body is an elongate cylindrical solid disposed with its axis parallel to the plate of the dielectric.

13. A device as claimed in any of the preceding claims, wherein the sensor layer is for protection covered in a tough, hard but flexible, thin outer layer.

14. A device as claimed in any of the preceding claims, wherein the charge sensing layer provides a voltage output, and is connected up to suitable means for detecting and acting upon that voltage, which means uses a voltmeter to measure the voltage across a storage capacitor charged up by an amplified version of the charge sensing layer's output.

15. A device as claimed in any of the preceding claims, wherein the means to launch the deformation wave into and along the piezoelectric layer is electrodes positioned at one edge of the layer and on either main surface thereof (so that they sandwich the layer between them), these electrodes being connectable to a source of electrical voltage that can be used to generate a

like voltage across the electrodes, so resulting in a piezoelectric deformation of the layer material.

16. A device as claimed in claim 15, wherein the applied voltage is in the form of a single sharp pulse of short duration, or a succession of such pulses, causing a like sharp, well-defined, single deformation wave, or a succession of such waves, to travel along the piezoelectric layer.

17. A device as claimed in any of the preceding claims, wherein that layer edge opposite where the wave is to be launched is constructed with a wedge shape, and there is placed around the wedge a wave-absorbent buffer.

18. A device as claimed in claim 17, wherein the buffer is formed of indium or an alloy thereof.

19. A device as claimed in any of the preceding claims, wherein the time-based sensor output is correlated with the time-based deformation wave/charge packet position, so there may be derived a measure of the magnitude of the applied pressure all along the device as a function of the position along the device, by an electronic gating arrangement.

20. A pressure sensor device as claimed in any of the preceding claims and substantially as described hereinbefore.

21. A mechanical hand (or like apparatus), whenever employing a pressure sensor device as claimed in any of the preceding claims.

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